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PULSATIONS IN LIQUID FLOW

By

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MEASUREMENT OF TURBULENT TEMPERATURE

PULSATIONS IN LIQUID FLOW

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The turbulent temperature pulsations
associated with the flow of liquid metal
and water in a tube have been measured.
Certain laws dealing with the variation
in the amplitude and frequency of
pulsations in turbulent liquid flow have
been established.

Under conditions of heat transfer the velocity pulsations of a
turbulent liquid flow result in turbulent temperature pulsations.
The experimental study of turbulent pulsations allows us to obtain
information regarding the internal structure of the flow and the
mechanism of heat transfer in the case of turbulent flow of a liquid.

The temperature in a liquid metal and a water flow was measured
by low-inertia movable thermocouples. The thermocouples were made of
chromel and alumel wires 0.1 mm in diameter covered with alundum
insulation, the thickness of the covering being 0.02 mm. The technique

of manufacturing and applying the alundum insulation is given in Ref. [1]. Two alundumized thermoelectrodes were placed in a thin-walled 0.5 x 0.1 capillary of 1Kh18N9T steel. One end of the capillary was welded together with the thermoelectrodes to form a hot thermocouple junction 0.5 mm in diameter. At the other end of the capillary the thermoelectrodes were fastened with a putty of magnesium oxide and liquid glass. In the experiments in water the thermocouple had an open junction 0.2 mm in diameter. Similar thermocouples were embedded in the wall of the test section: the thermocouples were set in grooves and covered with a layer of atomized metal. The hot thermocouple junctions were welded to the tube wall.

The temperature field in the liquid flow was measured simultaneously by two movable thermocouples situated on a single probe. The arrangement of the probe with the movable thermocouples and the test section is shown in Ref. [2]. The design of the test section and the system of control ensured smooth displacement of the thermocouples, as well as the possibility of fixing them at any point along the diameter of the tube (d = 29.3 mm). The position of the thermocouples in the tube was determined to an accuracy of $\pm$ 0.02 mm. The test section was arranged vertically. The heat flow was created by an electric heater, which consisted of four separate sections. This made it possible to determine the temperature field in the liquid flow at distances of 5, 10, 15, and 30 diameters from the origin of heating. In all of the experiments the length of the hydrodynamic-stabilization section was 30 diameters.

The thermocouple readings were recorded on the record sheets of high-speed automatic EPP-09 potentiometers of class 0.5, on which the time for a run through the entire scale was 1 sec. The upper limit

of the scale of the instrument was reduced to 0.5 millivolts; higher
thermoelectromotive forces were produced by a PPTN-1 low-resistance
potentiometer.

Earlier experiments [3] had shown that the temperature oscillations
recorded on the EPP-09 instrument were caused by the turbulent tempera-
ture pulsations in the flow and not by the action of various external
factors: oscillations in the flow rate, thermocouple vibration,
heating by a-c current, etc. The evolution of the temperature pulsa-
tions through time at fixed distances from the tube wall and the
processing of these pulsations enabled us to clarify a number of the
special features characteristic of turbulent flow.

Of primary importance is the experimental substantiation of the
fact that the amplitude of the temperature pulsations over the whole
cross section of the turbulent flow satisfies the normal distribution
law:

$$P = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\left(\frac{t'}{2\sigma}\right)^2 \right],$$ (1)

where $\sigma = \pm\sqrt{\frac{\Sigma(t')^2}{n-1}}$ is the rms value of the amplitude of the temperature
pulsations;

n is the entire number of positive and negative
pulsations t';

P is the probability density of a given amplitude.

The dependence of $P_1 = n_1/n$ (the ratio between the number of
pulsations with a given amplitude and the total number of pulsations)
on the amplitude is shown in Fig. 1 for some of the experiments.
The satisfactory agreement between the experimental data and Gauss'
law indicates that the temperature pulsations are of a random nature,
and therefore the time-averaged value of the temperature, the value
corresponding to the peak of the Gaussian curve, has the greatest

probability, while the maximum amplitudes of the pulsations do not exceed $\pm 3\sigma$. The averaged temperature has a low probability of only 6-12%, i.e., there exists a sufficiently broad spectrum with widely divergent amplitudes and frequencies, especially for moderate Re numbers. Unfortunately, because of the inertia of the EPP-09 instrument, we were not successful in determining the frequency characteristics of the turbulent temperature pulsations.

With a change in the Re number the shape of the temperature profile and the amplitude of the pulsations change; moreover, the nature of the temperature pulsations in the region of maximum amplitudes proved to be the same for liquid metals and water, although their thermal conductivities differ by a factor of 20-30. However, a difference was observed in the distribution of the pulsations along the diameter of the tube for liquid metals and water. In the case of liquid metals, which have a fairly smooth variation of the temperature gradient over the cross section of the tube, the maximum pulsations are observed approximately halfway between the center and the wall of the tube. In the case of water, which has an abrupt change in the temperature gradient in the region near the wall, the maximum pulsations are observed in the immediate vicinity of the wall. In the experiments with water, in the case of low Re numbers, a decrease in the amplitude of the pulsations could be observed when approaching right up to the wall.

Such a variation in the amplitude of the temperature pulsations along the radius of the tube qualitatively agrees with the hypothesis that the magnitude of the turbulent temperature pulsations is proportional to the instantaneous value of the mixing length l' and the gradient of the averaged temperature field $d\bar{t}/dy$:

$$t' \sim l' \frac{dt}{dy},$$

or for averaged values

$$\sigma \sim l \frac{\overline{dt}}{dy}, \tag{2}$$

where y is the distance from the tube wall, mm;

l is the mean mixing length.

With an increase in the Re number the region of maximum pulsations shifts toward the wall, since the shape of the temperature profile in the liquid flow changes, due to an increase in the turbulent heat conduction. This is apparent from an analysis of the experimental data for liquid metal. As the Re numbers increase, the shape of the temperature profile for liquid metal approaches the shape of the profile for water.
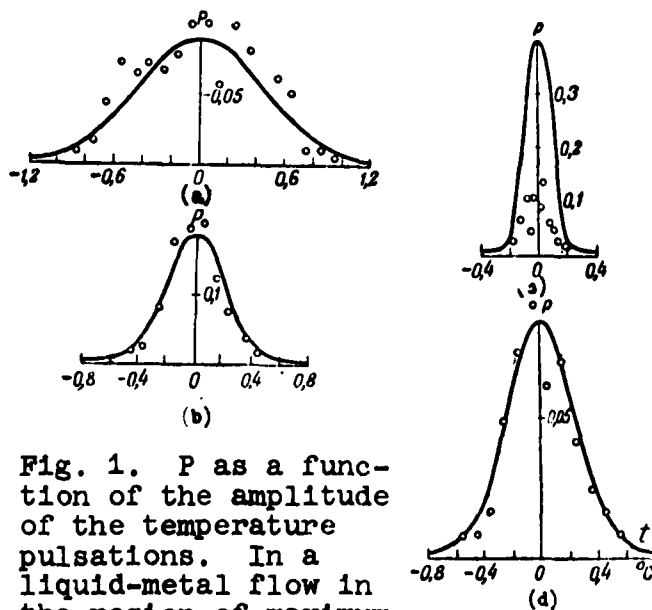
The position of the region of maximum amplitudes was found from the experimental data and compared with the results of calculation in accordance with the right side of formula (2). The temperature gradients were determined from the temperature profile, which had been obtained by us in experiments with liquid metal and was averaged over the cross section of the tube. The value of l was taken in accordance with Nikuradze's data, which were obtained from the averaged velocity profile:

Fig. 1. P as a function of the amplitude of the temperature pulsations. In a liquid-metal flow in the region of maximum amplitudes: a) Re = 2.4 · 10^4; b) Re = 2.3 · 10^5. In the tube wall: c) for water flow Re = 0.8 · 10^4; d) for liquid-metal flow Re = 2.4 · 10^4. The curves are plotted according to Gauss' formula (1).

$$l = \sqrt{\frac{\tau}{r}} \left(\frac{du}{dy}\right)^{-1} = r_0 \left[0{,}14 - 0{,}08\left(1 - \frac{y}{r_0}\right)^2 - \right.$$
$$\left. - 0{,}06\left(1 - \frac{y}{r_0}\right)^4\right]. \tag{3}$$

The experimental (curve 1) and the theoretical (curve 2) data agree with respect to the position of the maximum pulsation amplitude (Fig. 2). This is probably due to the fact that a proportionality exists between l, calculated from formula (3) and the value of $\sigma/r_0 (d\bar{t}/dy)^{-1}$, obtained by processing the data on the temperature pulsations. However, marked temperature pulsations exist on the axis and on the wall of the tube, although it follows from formula (2) that $t_1 = 0$ in these cases . Consequently, zero values of the averaged temperature gradient at local points do not lead to the absence of temperature pulsations.

By analogy with the concept of "intensity of velocity pulsations" [4], let us introduce a new concept "intensity of temperature pulsations", which may be expressed as the ratio between the rms amplitude and the thermal head: $\sigma/(t_w - \bar{t}_l)$.

This quantity varies over the cross section of the tube in the same way as does the value of σ. With an increase in the Re number from $2 \cdot 10^4$ to $2 \cdot 10^5$, the intensity of the temperature pulsations drops at all points in the turbulent flow (Fig. 3). We should expect the intensity of the temperature pulsations to have a maximum value in the range of Re numbers from 2,300 to 20,000, since there are no pulsations in the case of laminar flow.

Fig. 2. Variation of the rms amplitude of the temperature pulsations over the radius of the tube.
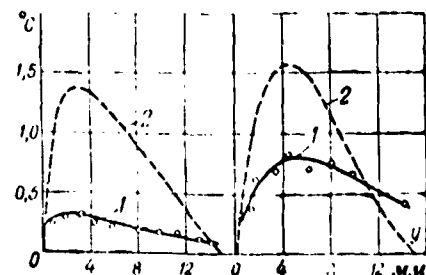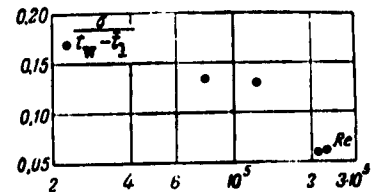a) Re = $2.1 \cdot 10^5$;   b) Re = $2.4 \cdot 10^4$.

Fig. 3. Variation of the intensity of the temperature pulsations with an increase in the Re number, when $y/r_0 = 0.5$.

In the experiments in water, conducted at low Re numbers, we were able to penetrate with the thermocouple the supposed laminar layer, the thickness of which is 0.4 to 0.5 mm at these Re numbers, according to semiempirical theories of turbulence. It was possible to set the thermocouple junction at a minimum distance from the wall $y = 0.1$ mm. Three temperature measurements were made in the wall layer ($y = 0.1$; 0.2; and 0.3 mm). One measurement in the transition region ($y = 1.2$ mm), and the others in the turbulent core of the flow. The shape of the temperature pulsations at various distances from the wall, as well as that of the temperature pulsations in the wall itself, is presented in Fig. 4. The thermocouple was embedded in the wall at a distance of 0.4 mm from the heat-transfer surface. In addition to the temperature pulsations in the turbulent core, there also exist pulsations in the immediate vicinity of the wall in the laminar layer and in the wall of the tube. The rms amplitude and mean frequency of the temperature pulsations remain unchanged over the major portion of the wall region. It is possible that no stable laminar layer exists, as was assumed in classical theories of turbulence. It may be assumed that the laminar layer is continuously changing in a random way, and its thickness, obviously, can be characterized by some statistical average value. Therefore, even in the case of a steady heat input, the process of heat transmission through the liquid layer against the wall and the heat-transfer surface is quasi-steady, just as in the turbulent core.

It should be noted that the laminar layer apparently does not vanish entirely, but always maintains a certain thickness at the wall itself, since the temperature pulsations in the tube wall do not reflect the amplitude and frequency characteristics of the pulsations in the wall layer, expecially in the experiments with water. In the case of water flow, the temperature pulsations in the wall are considerably less than the pulsations in the wall layer; moreover, there are no pulsations of high amplitude. However, in the case of liquid-metal flow the pulsations in the wall layer and those in the wall differ little. This is obviously due to the fact that in the remaining portion of the laminar layer there occurs a significant dampening of the amplitude of the pulsations in the case of water and an insignificant decrease in the amplitude in the case of liquid metal. Therefore the amplitudes of the pulsations in the tube wall in the case of liquid-metal flow continue to satisfy Gauss' law, while in the case of a water flow they are not governed by this law at all (cf. Figs. 1c and d). The difference in the degree of damping of pulsations in the case of water and liquid metal may be caused by the different values of the coefficient of thermal diffusivity ($\sim 2 \cdot 10^{-7}$ and $\sim 10^{-5}$ m^2/hr, respectively).
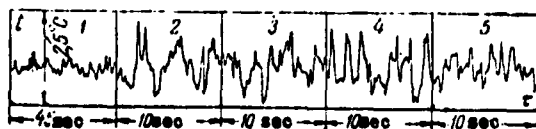

Fig. 4. Development of temperature pulsations in a liquid at various distances from the wall and in the wall of the tube for Re = 6, 700.

1) wall; 2) $y = 0.1$ mm; 3) $y = 0.2$ mm; 4) $y = 0.3$ mm; 5) $y = 1.2$ mm.

A calculation of the damping of the temperature waves according to the formula

$$\frac{A(y)}{A_\bullet} = e^{-\sqrt{\frac{\omega}{a}} \cdot y} \qquad (4)$$

shows that at a pulsation frequency $\omega = 1$ cps and a layer thickness $y = 0.2$ mm the amplitude of the pulsations decreases by a factor

of more than 2 in water, but by only 10% in liquid metal. For pulsations with higher frequencies the decrease in the amplitude will be more pronounced.

Turbulent temperature pulsations were measured for different heat flows $q = (0.1 -5) \cdot 10^4$ kcal/m²hr. It was noted that the amplitude of the temperature pulsations increases with an increase in the heat flow; however, the quantitative relationships involved in this case are still not clear. According to formula (2), we can expect that the amplitude of the temperature pulsations will depend on the value of the heat flow, as does the local temperature gradient.

A number of the experiments in water were conducted at low velocities, when the Re number was below critical. At these Re number turbulent temperature pulsations disappear completely; however, weak temperature oscillations continue in the central portion of the flow at a very low frequency. These temperature oscillations may be ascribed to natural convection in the liquid; they increase with an increase in the heat load. The temperature oscillations are absent in a fairly broad region near the wall and in the wall itself. With an increase in the velocity, after the Re number reaches 2,300, turbulent temperature pulsations of low amplitude and frequency begin to appear. For higher Re numbers (Re = 10⁴) the pulsations assume the form characteristic of developed turbulent flow (Fig. 5).

The variation in the mean frequency of the temperature pulsations in the liquid flow and in the tube wall during an increase in the R number is shown in Fig. 6. The mean frequency of the pulsations increases sharply from zero values at Re = 2,000 up to ~ 1 cps at Re = 2,300, thereby indicating the occurrence of turbulent flow. It is interesting to note that at the inception of turbulent flow there

is no difference between the mean frequency of the temperature pulsations in the tube wall and in the region near the wall in the case of water flow. With an increase in Re to 10^4 a difference appears.

Experimental data obtained for the flow of liquid metal at the inlet section of the tube enabled us to ascertain the nature of the origin of turbulent temperature pulsations in the stabilization of the temperature profile over the cross section of the tube. Hydrodynamic stabilization of flow was maintained in these experiments, i.e., the velocity pulsations in the liquid flow remained unchanged. At small Re numbers (Re $\approx 10^4$), when the temperature profile has already been formed, turbulent pulsations are observed over the whole cross section of the tube at a distance of 5d from the origin of heating. When Re $\geq 5 \cdot 10^4$ the temperature profile at the same distance is undergoing no stabilization at all. In the central part of the flow the temperature gradient is equal to zero, and there are no turbulent temperature pulsations (Fig. 7). The absence of pulsations indicates that the mixing length is definitely less than the radius of the tube. At a distance of 10d from the beginning of heating a temperature profile begins to form in the center of the tube even at high Re numbers (Re $\approx 2 \cdot 10^4$); therefore turbulent pulsations are observed over the whole cross section of the tube (Fig. 8). In all cases in which there is heat flow through the wall temperature pulsations are observed in the wall.
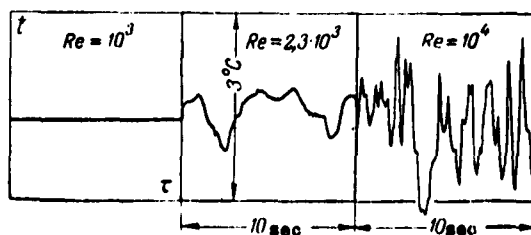

Fig. 5. The effect of the regime of a liquid flow on the temperature pulsations near the wall (y = 0.1).

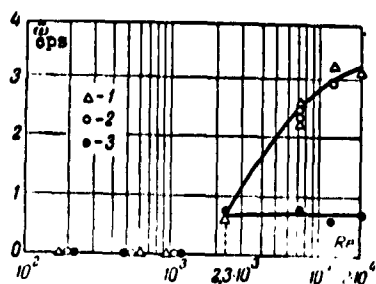1) Re = 10^3; 2) Re = $2.3 \cdot 10^3$;
3) Re = 10^4.

Fig. 6. Variation in the
·mean frequency of the
temperature pulsations with
an increase in the Re numbers
in liquid flow.

1) when y = 0.1 mm; 2) when
y = 1.2 mm; 3) in the tube
wall

The disappearance of the temperature pulsations in the case of breakdown of the stabilized temperature profile at considerable (up to 10d) distances from the end of heating was stud'ed in a number of experiments. The temperature pulsations in the wall and in the wall layer disappear because of the absence of a temperature gradient in this region. In the central portion of the flow a temperature gradient is still being maintained, and, consequently, pulsations in the temperature of the liquid still exist. Experiments, in which the heating was turned on and off, enabled us to follow chronologically the occurrence and disappearance of temperature pulsations in the liquid-metal flow and in the tube wall. Temperature pulsations arise in the flow within 5-7 seconds after the heating is switched on and assume the form characteristic of the given regime within 20 seconds. The pulsations are maintained in the flow for 15-20 seconds after the heating has been switched off, while they last for only 3 seconds in the tube wall.

The experiments which we have conducted have shown the fruitfulness of measurements of turbulent temperature pulsations in liquid flow. These measurements have enabled us to obtain certain information concerning the internal structure of the flow and the mechanism of turbulent heat transfer.

Due to the inertia of the EPP-09, the oscillations recorded on the record sheets of the instruments do not reflect completely the

entire spectrum of turbulent temperature pulsations. However, it is known from the literature that the major part of the kinetic energy of the pulsations is contained in the frequency range below 3 cps, while the role of pulsations with frequencies higher than 20 cps in the energy transfer is negligibly small [5]. It may be expected that pulsations with frequencies below 3 cps also play the major role in the transfer of heat energy. In this frequency range the EPP-09 can record the temperature pulsations with only slight distortion.

The recording of temperature pulsations by existing types of oscillographs has no great advantages, since the highly sensitive loops are capable of registering only low frequencies. Therefore, for further comprehensive study of pulsations and in order to obtain quantitative relationships, it is necessary to develop improved low-inertia instruments and thermocouples capable of recording the whole spectrum of turbulent temperature pulsations.
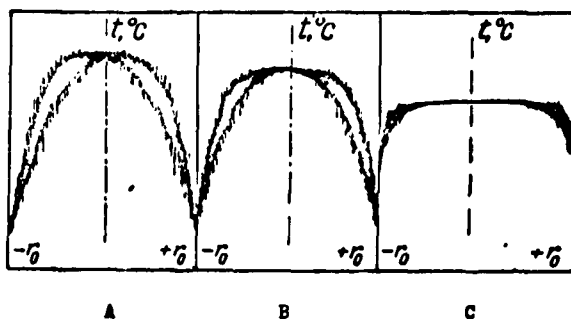

Fig. 7. Temperature profile along the radius of the tube at a distance of five diameters from the beginning of heating.
a) Re = 10^4; q = 19,500 kcal/m^2 · hr; b) Re = 2 · 10^4, q = 21,200 kcal/m^2 · hr; c) Re = = 8.7 · 10^4, q = 43,800 kcal/m^2 · hr.
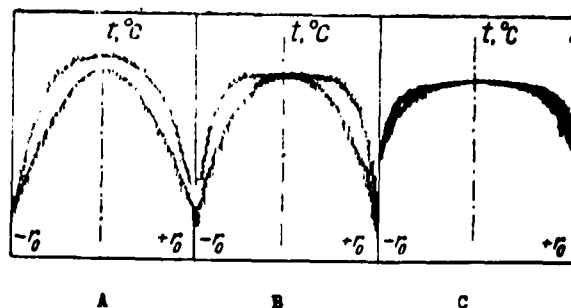
Fig. 8. Temperature profile along the radius of the tube at a distance of 10d from the beginning of heating.
a) Re = 1.5 · 10^4, q = 15,100 kcal/m^2 · hr; b) Re = 6.2 · 10^4 q = 33,000 kcal/m^2 · hr; c) Re = = 2.10^5, q = 36,600 kcal/m^2 · hr.

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